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Study on the Stability of aquiclude in the Close-Distance Coal Seams Repeated Mining in the Jurassic Coalfield of Northern Shaanxi

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Abstract. The aquifer in the Salawusu Formation is extensively distributed within the Jurassic coalfield of northern Shaanxi, China. However, the fracture development in overlying strata induced by repeated mining of close-distance coal seams and the stability of the aquiclude remain unclear. Combining the methods of statistical analysis, numerical simulation, and theoretical analysis, the stability criterion of the aquiclude was established. Results show that for single coal seam mining, the development height of mining-induced fractures is proportional to the mining height. In contrast, the ratio of fracture development height to mining height (r) shows no significant correlation with the mining height, typically ranging from 18-30. For repeated mining of close-distance coal seams, the r also exhibits no obvious correlation with the cumulative mining height, with a typical range of 10-25, which is lower than that observed in single-seam mining. The calculation methods for the development height of upward fractures and the development depth of downward fractures during repeated mining were given, and the stability criterion of aquiclude based on the development characteristics of mining-induced fractures is proposed. The research outcomes further enrich the strata control theory for water-preserving mining of close-distance coal seams in western China.

Keywords: Close-distance coal seams; repeated mining; water-preserving mining; fracture development; stability criterion of aquiclude.

1. Introduction

The Jurassic coalfield in northern Shaanxi is a crucial coal production base in China. Its coal seams are characterized by shallow burial depth, thin overlying bedrock, thick unconsolidated formations, and a fragile ecological environment. As mines transition from single coal seam mining to coal seam group mining, repeated mining activities result in increased total extraction coal seam thickness, leading to concentrated fracture development in the overlying strata at mining boundaries, Which poses a serious threat to the aquiclude stability. Aquifuge instability can trigger surface water depletion, underground water and sand inrushes, and ecological degradation, presenting particularly severe challenges to the preservation of the aquifer in the Salawusu Formation, Consequently, achieving water-preserving mining in close-distance coal seams has emerged as a core requirement for the green development of this region.

In recent years, based on the stability control of aquiclude in close-distance coal seams mining, scholars have conducted two main aspects of relevant research.The first focuses on the failure characteristics and stability of aquiclude in single coal seam mining. This research has clarified the definition of aquiclude and the failure characteristics of aquiclude, while also establishing a stability

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criterion for aquiclude in single coal seam mining[1-8]. The second strand focuses on the aquiclude stability during the mining of lower coal seams. Feng et al. proposed the concept of interlayer control aquiclude, and analyzed the effect of mining-induced damage on its stability[9]. Zheng et al. demonstrated that during the shallow buried close-distance coal seams mining, mining-induced fractures from different coal seam groups readily interconnect, leading to aquiclude failure[10]. Pan et al. analyzed the failure characteristics of overlying rock in close-distance coal seam mining with thin bedrock, and revealed the process by which overlying rock fracturing induces aquifer water inrush[11].

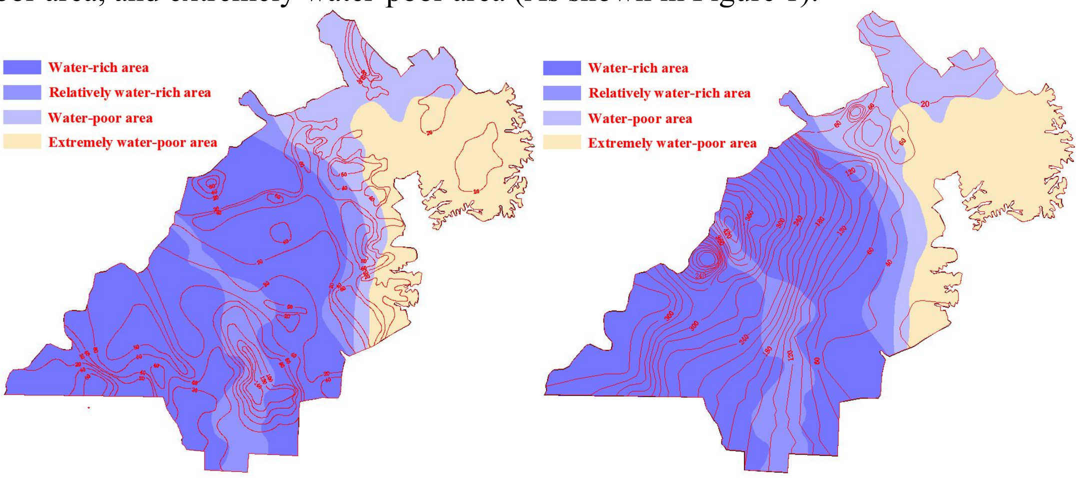
To date, extensive research has been conducted on aquiclude stability in single coal seam mining. The stability criteria for aquiclude has been established, and the strata control theory for water-preserving mining of single coal seam mining was proposed. However, research on aquiclude stability in close-distance coal seam mining remains limited, and the theory for aquiclude stability criteria based on fracture development models is still immature, Consequently, further research is urgently required.

2. Characteristics of Coal-Water Occurrence and Field-Measured laws of Mining-Induced Fractures in the Study Area

2.1 Characteristics of Coal-Water Occurrence in the Study Area

The 1-2, 2-2, and 3-1 coal seams are the primary minable seams in the Jurassic coalfield of northern Shaanxi. The 1-2 coal seam is widely distributed throughout the coalfield, with a typical thickness ranging from 1-3 m (and locally 3-5 m), its structure is simple, and is classified as a stable coal seam. The thickness of 2-2 coal seam ranges from 0.26-12.16 m, (averaging 6.5 m), and is classified as a stable medium-to-extra-thick coal seam.The thickness of 3-1 coal seam ranges from 0.18-4.01 m (averaging 2.48 m), it shows minimal thickness variation, has a simple structure, and is defined as a stable medium-thick coal seam. The interburden between the 1-2 and 2-2 coal seams typically ranges from 13.11-38.77 m (averaging 25 m), the interburden between the 2-2 and 3-1 coal seams typically ranges from 20.52-41.08 m (averaging 30 m). The coal seams display a characteristic burial depth pattern, shallow in the eastern areas and deep in the western areas, the shallowest burial depth (less than 40 m) occurs in the northeastern of the coalfield, while the deepest (over 500 m) is found in the southwestern of the coalfield.

The Jurassic coalfield in northern Shaanxi is characterized by coal-water symbiosis in the occurrence of coal seams and aquifer, where aquifer lie above coal seams. The dominant aquifer in the mining area is the Salawusu Formation aquifer, which is predominantly composed of fine and medium sand. Based on its distribution characteristics, the Salawusu Formation aquifer in this region is classified into four hydrogeological areas: water-rich area, relatively water-rich area, water-poor area, and extremely water-poor area (As shown in Figure 1).



(a) Thickness contours of the soil layer (b) Thickness Contours of the bedrock

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Figure 1 Distribution characteristics of the Salawusu Formation aquifer, soil layer, and bedrock

The thickness of the bedrock increases progressively from east to west, areas with bedrock thickness less than 50 m are primarily located in the Shenbei Mining Area and Xinmin, areas with 50-100 m thickness occur in the Zhongji-Yaozhen, areas with 100-250 m thickness are distributed in the Erlintu-Jinjitang, areas with thickness more than 250 m are primarily located in the west of the Erlintu-Xiaobaodang- Mengjiawan line. A weathered zone is ubiquitous above the bedrock, with a thickness ranging from 20-25 m. The aquiclude is primarily composed of the Quaternary Lishi Loess and the Neogene Hipparion Red Clay, with a thickness typically ranging from 20-175 m.

2.2 Field-Measured laws of Mining-Induced Fractures in Close-distance Coal Seams

After single coal seam and the repeated mining of close-distance coal seams, The development laws of overlying fractures in selected mines of the study area are summarized in Table 1. The development height variation of overlying fractures with mining height is shown in Figure 2.

As shown in Figures 2a and 2b, for single coal seam mining, the development height of mining-induced fractures is proportional to the mining height. In contrast, the ratio of fracture development height to mining height (r) shows no significant correlation with the mining height. Specifically, r typically ranges from 15-30, with the majority of values are 18-30. As shown in Figures 2c and 2d, after repeated mining of close-distance coal seams, due to the mined thickness increases, the development height of fractures increases, and it is proportional to the cumulative mining height of the two coal seams. Similarly, the r exhibits no significant correlation with the cumulative mining height, typically ranging from 10-30 (mostly 10-25), which is lower than that for single coal seam mining. Consequently, for coal seams of the same total thickness, slicing mining results in a lower development height of fractures compared to large-height mining.

Table 1. Field-measured statistics of mining-induced fractures in close-distance coal seams

Number	Mine/coal seam	Upper coal seam				Lower coal seam			
		Mining height /m	Bedrock thickness /m	Fracture zone height/ m	Caving zone height /m	Mining height /m	Interburden thickness/m	Fracture zone height/ m	Caving zone height /m
1	Hongliulin/4-2 coal seam	2.87	57.4	98.2	15.5	-	-	-	-
2	Jinjie/3-1 coal seam	3	60.8	68.3	9.1	-	-	-	-
3	Liangshuijingl/4-2 coal seam	3.12	37.2	64.2	30.2	-	-	-	-
4	Huangling/2 coal seam	3.2	549.7	68	18	-	-	-	-
5	Yuyang/2-2 coal seam	3.5	Buried depth 208	96.3	17.2	-	-	-	-
6	Daliuta/1-2 coal seam	3.95	Buried depth 89.2	89.2	13.5	-	-	-	-
7	Hanjiawan/2-2 coal seam	4.43	Buried depth 160	110	-	-	-	-	-
8	Hanglaiwan/4-2 coal seam	4.5	150	116	22.2	-	-	-	-
9	Yushuwan/2-2 coal seam	5	151.1	139	-	-	-		-
10	Jinjitan/2-2 coal seam	5.5	202	146	20.6	-	-	-	-
11	Zhangjiaomao/2-2 coal seam	5.6	117	166	37	-	-	-	-

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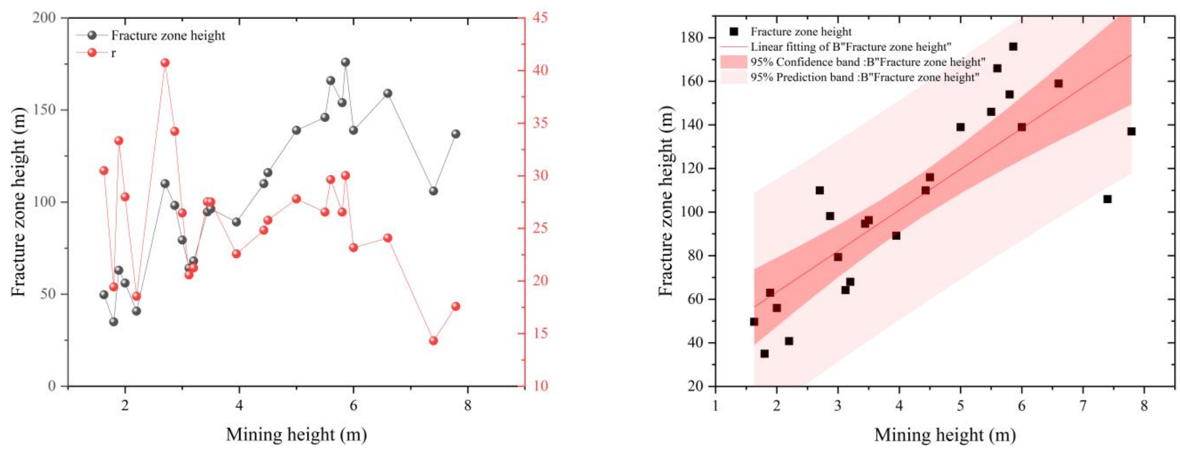
12	Ningtiata/2-2 coal seam	5.8	Buried depth 171	154	35.3	-	-	-	-
13	Caojiatan/2-2 coal seam	6	214	139	-	-	-	-	-
14	Buertai/4-2 coal seam	6.6	-	159	-	-	-	-	-
15	Bulianta/1-2 coal seam	7.4	207	106	35.1	-	-	-	-
16	Daliuta/5-2 coal seam	7.79	-	137	19.8	-	-	-	-
17	Halagou/1-2 Upper coal seam and 1-2 coal seam	1.63	38.3	49.7	9	1.7	9.04	60.4	13
18	Liangshuijing /4-2 coal seamand 4-3 coal seam	3	40.4	117	-	1	19.8	139.5	-
19	Hanjiawan/3-1 coal seam and 4-2 coal seam	2.7	50	110	17.6	1.9	37	150.2	13.8
20	Shigetai/1-2 coal seam and 2-2 coal seam	2.2	40.8	40.8	17.4	3.5	40.7	83.8	15.6
21	Longde/1-2 coal seam and 2-2 coal seam	1.8	110	35	15.1	4	50	100	32
22	Hongliulin/2-2 coal seam and 3-1 coal seam	3.44	30.1	94.7	15	3.05	28.5	126	16.5
23	Ningtiaota/1-2 coal seam and 2-2 coal seam	1.89	81.7	63	12	4.6	33.3	158.6	23.6
24	Jinjie/3-1 coal seam and 4-2 coal seam	3.2	63	52.6	13	3.5	20	73	14
25	Halagou/2-2 coal seam and 3-1 coal seam	6	Buried depth 82	82	-	1.8	46.14	128.14	-
26	Xiaobaodang/2-2 coal seam and 3-1 coal seam	5.86	254.1	176	40.1	2	33.2	233.5	9
27	YubeiMine/1-2 coal seam and 2-2 coal seam	2	253.6	56	7	6	39.9	196	16
28	Buertai/2-2 coal seam and 4-2 coal seam	3	Buried depth 335	79.4	21	6.6	71.2	158.5	34.7



(a) Development height of fractures in single seam mining (b) Correlation relationship

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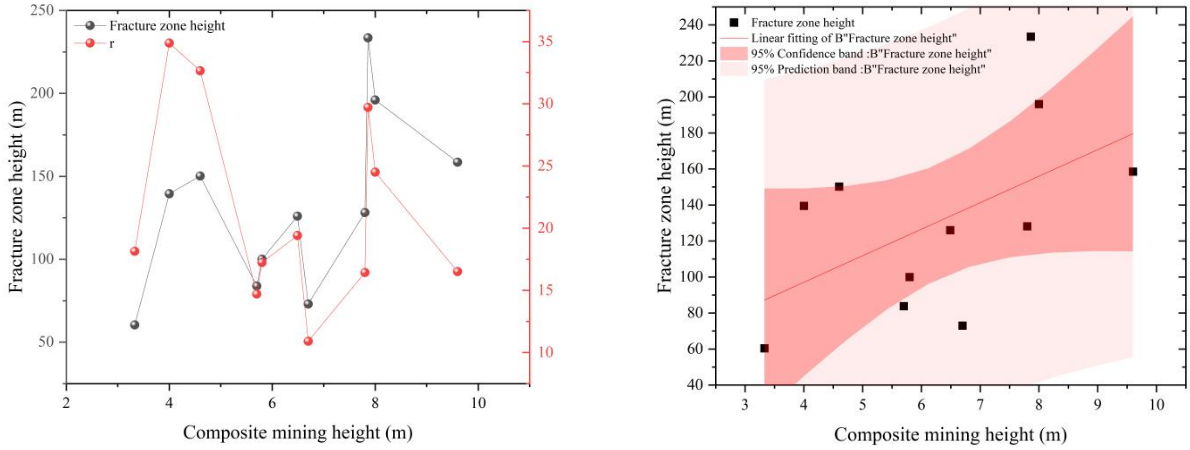


(c) Development height of fractures in repeated mining (d) Correlation relationship

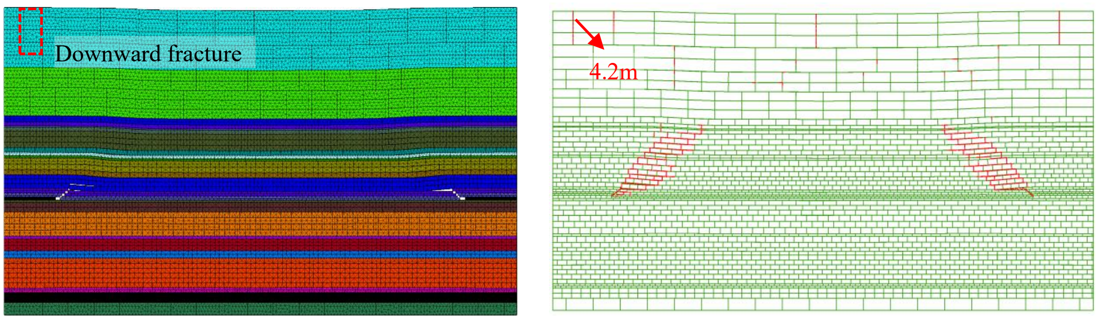
Figure 2 Variation of fracture development height with coal seam mining height in single seam and close-distance seam mining

3. Simulation Study on Fracture Development Laws in Close-Distance Coal Seam Mining

The 4-2 and 5-2 coal seams in Hongliulin Coal Mine are classified as shallow buried close-distance coal seams mining. The thickness of 4-2 coal seam is 2.05 m and its buried depth is 121.6 m. Specifically, the thickness of bedrock is 51.8 m, and the thickness of soil layer is 69.8 m. The thickness of 5-2 coal seam is 6.5 m, and the interburden between the two coal seams is 58.8 m. The aquifer in the area is the Salawusu Formation, which is widely distributed regionally.

The development laws of overburden fractures and damage characteristics of aquiclude after 4-2 coal seam mining are shown in Figure 3. The ordinate represents the development height of upward fractures and depth of downward fractures of overburden fractures. Upward fractures extend to the soil layer, reaching a height of 52.6 m, while downward fractures with a depth of 4.2 m are formed on the open-off cut side. Mining-induced fractures fail to penetrate the aquiclude, and the aquiclude remains stable.

Figure 4 shows the fracture development laws in the overburden strata and the failure characteristics of the aquiclude after 5-2 coal seam mining. During the mining of the 5-2 coal seam, stress redistribution ahead of the advancing working face caused fracturing and caving of the interburden strata. As this damage propagated upwards into the goaf of the overlying 4-2 coal seam, pre-existing mining-induced fractures (both upward and downward fractures) were reactivated by the repeated mining disturbance. After 5-2 coal seam mining, the upward fractures and the downward fractures are interconnected, and the upward fractures develop to the ground surface, reaching a height of 182.45 m, while multiple downward fractures formed in the soil layer, with a maximum depth of 22.8 m, the aquiclude is instability.



(a) Overburden caving characteristics (b) Mining-induced fractures

Figure 3. Fracture development and aquiclude damage characteristics of 4-2 coal seam mining

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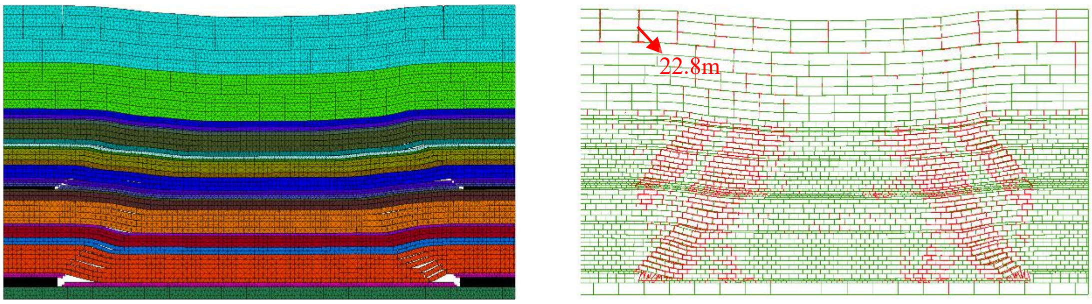

(c) Overburden caving characteristics (b) Mining-induced fractures

Figure 4. Fracture development and aquiclude damage characteristics of 5-2 coal seam mining

4. Stability Criteria of Aquicludes Based on the Development Laws of Mining-Induced Fractures

After mining the upper single coal seam, caving zone and fracture zone form in the overlying strata. During the close-distance coal seam repeated mining, the original fractures caused by the upper single coal seam mining activation and development, the width of fractures increase, and its development height also increases. Therefore, predicting the development height of upward fractures requires accounting for the mining height of the upper and lower seams, interburden thickness, and rock stratum caving characteristics. These factors are integrated into a cumulative mining height. Accordingly, the authors performed regression analysis on upward fracture development height data from coal seam mining in 27 mines within the study area. Referring to the basic form of Empirical Formula 1 in the Code for Mining Under Buildings, Water Bodies and Railways [12], a univariate linear regression model was established for prediction. A prediction formula for the development height of upward fractures during repeated mining of close-distance coal seams is proposed:

$$H_s = \frac{100\Sigma M}{-0.32\Sigma M + 6.27} \pm 21.1 \tag{1}$$

Where, ΣM is cumulative mining height, m.

Under the conditions of shallow buried and large mining height, downward fractures may form at the top of the aquiclude. The occurrence of downward fractures induced by coal seam mining depends on the relationship between the maximum horizontal tensile deformation ε_0 at the top of the aquiclude and the ultimate horizontal deformation ε_j of the soil mass.Specifically, when $\varepsilon_0 \geq \varepsilon_j$, the downward fractures form, when $\varepsilon_0 < \varepsilon_j$, the downward fractures can not form. Values of ε_0 and ε_j can be calculated using the formulas below [13]:

$$\varepsilon_0 = 1.52 \frac{bq\Sigma M \cos\alpha \tan\beta}{H} \tag{2}$$

$$\varepsilon_j = 2c \tan\left(45° - \frac{\varphi}{2}\right) \frac{1-\mu^2}{E} \tag{3}$$

Once the aquiclude cracks, downward fractures develop downward. Accordingly, a method for predicting the development depth of mining-induced downward fractures is proposed below:

$$H_x = \frac{\sqrt{3}\left[\frac{E\varepsilon_0}{1-\mu^2} - c\left(1 + 2Y\tan\left(45° - \frac{\varphi}{2}\right)\right)\right] 100\Sigma M}{2\gamma} \tag{4}$$

Where, b is the horizontal movement coefficient. q is the subsidence coefficient. α is the dip angle of coal seam, °. $\tan\beta$ is the tangent of the main influence angle. H is the coal seam buried depth, m. c is the soil cohesion, MPa. φ is the soil internal friction angle, °. μ is the soil Poisson's ratio. E is the soil elastic modulus, MPa. Y is the shape coefficient, Y=1. γ is the unit weight of the water-resisting soil, kN/m^3 .

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Considering the safety thickness of the aquiclude, when the aquiclude thickness ⩾ development height of upward fracture + development depth of downward fractures + safety thickness, the aquiclude can remain stable. Conversely, it is unstable. Therefore, the stability criterion of the aquiclude under repeated mining is proposed as follows:

$$H_g \geq H_s + H_x + (3-5)\ \Sigma M \tag{5}$$

Where, H_g is the aquiclude thickness, m.

5. Conclusion

(1) For single coal seam mining, the development height of mining-induced fractures is proportional to the mining height. In contrast, the ratio of fracture development height to mining height (r) shows no significant correlation with the mining height, typically ranging from 18-30. For repeated mining of close-distance coal seams, the r also exhibits no obvious correlation with the cumulative mining height, with a typical range of 10-25, which is lower than that observed in single-seam mining.

(2) By conducting regression analysis on the development height data of upward fractures induced by coal seam mining in mines within the study area, a prediction formula for the development height of upward fractures under repeated mining of close-distance coal seams is established. Fracture mechanics is applied to analyze the calculation method for the development depth of downward fractures.

(3) The stability criterion of the aquiclude under repeated mining is proposed. When the aquiclude thickness ≥ development height of upward fracture + development depth of downward fractures + safety thickness, the aquiclude can remain stable. Conversely, it is unstable.

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